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# Nonlinear Oscillation of Functional Differential Equations with Deviating Argument (Qualitative Theory of Solutions in Functional Differential Equations)

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NONLINEAR OSCILLATION OF FUNCTIONAL DIFFERENTIAL

EQUATIONS WITH DEVIATING ARGUMENT

Hiroshi ONOSE

1. INTRODUCTION

In this talk we consider the nonlinear second order functional differential equation with complicated deviating argument

$$(1) \quad [r(t)y'(t)]' + f(y(h(t)), t) = 0.$$

The conditions we always assume for  $r$ ,  $g$ ,  $f$  are as follows:

- (a)  $r(t)$  is continuous and positive for  $t \geq \alpha$ ;
- (b)  $h(t) = g(t) + k(y(t))^2$ , where  $k$  is a nonnegative constant,  $g(t)$  is continuous for  $t \geq \alpha$  and  $g(t) \geq t$ ;
- (c)  $f(y, t)$  is continuous for  $|y| < \infty$ ,  $t \geq \alpha$ , and  $yf(y, t) > 0$  for  $y \neq 0$ ,  $t \geq \alpha$ .

Equation (1) is called superlinear if, for each fixed  $t$ ,  $f(y, t)/y$  is nondecreasing in  $y$  for  $y > 0$  and nonincreasing in  $y$  for  $y < 0$ . It is called strongly superlinear if there exists a number  $\sigma > 1$  such that, for each fixed  $t$ ,  $f(y, t)/|y|^\sigma \text{sgn } y$  is nondecreasing in  $y$  for  $y > 0$  and nonincreasing in  $y$  for  $y < 0$ . Equation (1) is called sublinear if, for each fixed  $t$ ,  $f(y, t)/y$

is nonincreasing in  $y$  for  $y > 0$  and nondecreasing in  $y$  for  $y < 0$ . It is called strongly sublinear if there exists a number  $\tau < 1$  such that, for each  $t$ ,  $f(y,t)/|y|^\tau \operatorname{sgn} y$  is nonincreasing in  $y$  for  $y > 0$  and nondecreasing in  $y$  for  $y < 0$ . In what follows we restrict our discussion to those solutions  $y(t)$  of (1) which exist on some ray  $[T_y, \infty)$  and satisfy  $\sup \{|y(t)| : t \geq T\} > 0$  for every  $T > T_y$ . Such a solution is said to be oscillatory if the set of its zeros is not bounded; otherwise, it is said to be nonoscillatory. Equation (1) itself is called oscillatory if all of its solutions are oscillatory. An important special case of (1) is the following generalized Emden-Fowler equation

$$(2) \quad [r(t)y'(t)]' + p(t)|y(h(t))|^\gamma \operatorname{sgn} y(h(t)) = 0$$

where  $\gamma$  is a positive constant and  $p(t)$  is a continuous and nonnegative function on  $[\alpha, \infty)$ . The problem of oscillation of solutions of functional differential equations with deviating arguments has received a wide attention during the last several years. Most of the literature, however, has been devoted to the investigation of differential equations with retarded arguments, and little is known about the oscillatory behavior of differential equations with complicated deviating arguments.

The main purpose of this paper is to undertake a first attempt in the direction of establishing oscillation and nonoscillation results of all solutions for equation (1) with complicated argument which seem to be interesting in the engineering. To do this, we refer to the papers [1-5,7], Hino [12] and

the book([6], p. 3). Especially, we get a hint for this problem from an equation

$$\frac{du(t)}{dt} = u(t)(1-u(t-h(t,u(t))))$$

in the book([6], p. 3).

## 2. THE MAIN RESULTS

In what follows we use the function  $R(t)$  defined by

$$R(t) = \int_{\alpha}^t r(s)^{-1} ds, \quad \text{and} \quad \lim_{t \rightarrow \infty} R(t) = \infty.$$

THEOREM 1. Let (1) be either superlinear or sublinear.  
Then, a necessary and sufficient condition for (1) to have a  
bounded nonoscillatory solution is that

$$(3) \quad \int_{\alpha}^{\infty} R(t) |f(c, t)| dt < \infty \quad \text{for some } c \neq 0.$$

PROOF. (Necessity) Let  $y(t)$  be a bounded nonoscillatory solution of (1). Multiplying (1) by  $R(t)$  and integrating from  $t_1$  to  $t$ , we have

$$\begin{aligned} R(t)r(t)y'(t) - y(t) - R(t_1)r(t_1)y'(t_1) + y(t_1) \\ + \int_{t_1}^t R(s)f(y(h(s)), s)ds = 0, \end{aligned}$$

which implies (3).

(Sufficiency) Consider the integral equation

$$(4) \quad y(t) = a + \int_T^t R(s)f(y(h(s)),s)ds + R(t) \int_t^\infty f(y(h(s)),s)ds.$$

A solution of (4) is a solution of equation (1). By using Schauder's fixed point theorem, we have a solution  $y(t)$  of (4) which tends to a finite limit as  $t \rightarrow \infty$ .

THEOREM 2. Let (1) be strongly superlinear. Then, a necessary and sufficient condition for (1) to be oscillatory is that

$$(5) \quad \int^\infty R(t)|f(c,t)|dt = \infty \text{ for all } c \neq 0.$$

THEOREM 3. Let (1) be strongly sublinear. Suppose that  $f(y,t)$  is nondecreasing in  $y$  for each  $t$ . If

$$(6) \quad \int^\infty |f(cR(t),t)|dt = \infty \text{ for all } c \neq 0,$$

then (1) is oscillatory.

EXAMPLE. Consider the functional differential equation with complicated argument

$$[t^{-2}y'(t)]' + 2\frac{2}{3}t^{-\frac{11}{3}}[y(t^2 + y(t)^2)]^{\frac{1}{3}} = 0,$$

Which has a nonoscillatory solution  $y(t) = t$ . As is easily seen (6) is violated.

### 3. THE MORE GENERAL CASE

We consider the case  $h(t) = g(t) + s(y(t),y'(t))$ , where

$s(u,v)$  is continuous on  $R^2$  and  $s(u,v) \geq 0$  for all  $(u,v) \in R^2$ , and  $g(t) \geq t$ .

$$(7) \quad [r(t)y'(t)]' + f(y(g(t) + s(y(t), y'(t))), t) = 0.$$

THEOREM 4. Let (7) be strongly superlinear. Then, a necessary and sufficient condition for (7) to be oscillatory is (5).

$$4. \quad \text{THE CASE WHERE} \quad \int_{\alpha}^{\infty} r(t)^{-1} dt < \infty$$

We use the function  $\rho(t)$  defined by  $\rho(t) = \int_t^{\infty} r(s)^{-1} ds$ .

THEOREM 5. Let (1) be strongly superlinear. Suppose that

$$(8) \quad \int_0^{\infty} |f(c\rho(t+M), t)| dt = \infty \text{ for all } c \neq 0,$$

and  $h(t) = t + s(y(t), y'(t))$ ,  $0 \leq s(u,v) \leq M$  for all  $(u,v) \in R^2$  and  $M$  is a constant. Then (1) is oscillatory.

PROOF. Suppose there exist a nonoscillatory solution  $y(t)$  of (1). Without loss of generality we may suppose that  $y(t) > 0$  for  $t \geq t_0$ . By adding some modifications to the proof part of Kusano and the present speaker ([7], pp. 548-549), we have that

$$(\sigma-1)k^{-\sigma} \int_{t_2}^t f(k\rho(h(s)), s) ds \leq [-r(t_2)y'(t_2)]^{1-\sigma} - [-r(t)y'(t)]^{1-\sigma},$$

where  $k = -r(t_2)y'(t_2)$ .

From this, we obtain

$$\int_{t_2}^{\infty} f(k\rho(s+M), s) ds < \int_{t_2}^{\infty} f(k\rho(h(s)), s) ds < \infty,$$

which implies a contradiction to (8).

## 5. THE HIGHER ORDER CASE

We consider the higher order equation

$$(9) \quad L_n y(t) + H(t, y(h_1(t)), \dots, y(h_m(t))) = f(t),$$

where  $n \geq 2$ ,  $h_i(t) = g_i(t) + s_i(y(t), y'(t), \dots, y^{(n-1)}(t))$ ,  $g_i(t) \geq t$ ,  $1 \leq i \leq m$ ,  $s_i(y_1, y_2, \dots, y_n)$  is continuous on  $R^n$ ,  $s_i(y_1, y_2, \dots, y_n) \geq 0$  for any  $(y_1, y_2, \dots, y_n) \in R^n$ , and  $L_n$  denotes the differential operator

$$(10) \quad L_n = \frac{1}{p_n(t)} \frac{d}{dt} \frac{1}{p_{n-1}(t)} \frac{d}{dt} \cdots \frac{d}{dt} \frac{1}{p_1(t)} \frac{d}{dt} \frac{1}{p_0(t)}.$$

We assume that  $p_i, f, g_i: [a, \infty) \rightarrow R$  and  $H: [a, \infty) \times R^m \rightarrow R$  are continuous and  $p_i(t) > 0$ . (Cf. Singh and Kusano[9])

### A) MAIN RESULT

Consider the case

$$(11) \quad \int_a^{\infty} p_i(t) dt = \infty \quad \text{for } 1 \leq i \leq n-1.$$

A differential operator  $L_n$  defined by (10) is said to be in canonical form if condition (11) is satisfied. It is shown that any differential operator of the form (10) can be represented in canonical form in an essentially unique manner. We will use the following notations:

$$(12) \quad \begin{cases} I_0 = 1, \\ I_k(t, s; p_{i_k}, \dots, p_{i_1}) = \int_s^t p_{i_k}(r) I_{k-1}(r, s; p_{i_{k-1}}, \dots, p_{i_1}) dr \end{cases}$$

and

$$(13) \quad J_1(t, s) = p_0(t) I_1(t, s; p_1, \dots, p_1), \quad J_1(t) = J_1(t, a),$$

$$(14) \quad K_1(t, s) = p_n(t) I_1(t, s; p_{n-1}, \dots, p_{n-1}), \quad K_1(t) = K_1(t, a),$$

for  $i_k \in \{1, 2, \dots, n-1\}$ ,  $1 \leq k \leq n-1$ , and  $t, s \in [a, \infty)$ .

THEOREM 6. Suppose (11) holds and there exists a continuous function  $q: [a, \infty) \rightarrow [0, \infty)$  such that

$$(15) \quad |H(t, y_1, \dots, y_m)| \leq q(t) \text{ for } (t, y_1, \dots, y_m) \in [a, \infty) \times \mathbb{R}^m$$

holds. Suppose that

$$\int_a^\infty K_{n-1}(t) q(t) dt < \infty \quad \text{and} \quad \int_a^\infty K_{n-1}(t) |f(t)| dt < \infty.$$

Then every oscillatory solution  $y(t)$  of (8) satisfies

$$\lim_{t \rightarrow \infty} [y(t)/p_0(t)] = 0.$$



B) NON CANONICAL  $L_n$ 

We consider the case where  $L_n$  in (9) is not in canonical form. Any differential operator of the form (10) can be represented in canonical form and the representation is essentially unique. More precisely, if  $L_n$  is given by (10) and if condition (11) is not satisfied, then  $L_n$  can be rewritten as

$$(16) \quad L_n = \frac{1}{\widetilde{p}_n(t)} \frac{d}{dt} \frac{1}{\widetilde{p}_{n-1}(t)} \frac{d}{dt} \cdots \frac{d}{dt} \frac{1}{\widetilde{p}_1(t)} \frac{d}{dt} \frac{\cdot}{\widetilde{p}_0(t)},$$

so that

$$(17) \quad \int_a^\infty \widetilde{p}_i(t) dt = \infty, \quad 1 \leq i \leq n-1,$$

and the  $\widetilde{p}_i(t)$ ,  $0 \leq i \leq n$ , are determined up to positive multiplicative constants with product 1. By a principal system for  $L_n$  is meant a set of  $n$  solutions  $Y_1(t), \dots, Y_n(t)$  of  $L_n y(t) = 0$  which are eventually positive and satisfy

$$(18) \quad \lim_{t \rightarrow \infty} \frac{Y_i(t)}{Y_j(t)} = 0 \quad \text{for } 1 \leq i < j \leq n.$$

In case  $L_n$  is in canonical form the set of functions

$$(19) \quad \{J_0(t), J_1(t), \dots, J_{n-1}(t)\}$$

defined by (13) is a principal system for  $L_n$ , and the set of functions

$$(20) \quad \{K_0(t), K_1(t), \dots, K_{n-1}(t)\}$$

defined by (14) is a principal system for the operator

$$(21) \quad M_n = \frac{1}{p_0(t)} \frac{d}{dt} \frac{1}{p_1(t)} \frac{d}{dt} \cdots \frac{d}{dt} \frac{1}{p_{n-1}(t)} \frac{d}{dt} \frac{1}{p_n(t)},$$

which is also in canonical form. For a general operator  $L_n$  a principal system can easily be obtained by direct integration of the equation  $L_n y(t) = 0$ . A basic property of principal system is that if  $\{Y_1(t), \dots, Y_n(t)\}$  and  $\{\tilde{Y}_1(t), \dots, \tilde{Y}_n(t)\}$  are any two principal systems for the same  $L_n$ , then the limits

$$(22) \quad \lim_{t \rightarrow \infty} \frac{\tilde{Y}_i(t)}{Y_i(t)} > 0, \quad 1 \leq i \leq n,$$

exist and are finite.

THEOREM 7. Suppose that there exists a continuous function  
 $q: [a, \infty) \rightarrow \mathbb{R}$  such that

$$|H(t, y_1, \dots, y_m)| \leq q(t) \text{ for } (t, y_1, \dots, y_m) \in [a, \infty) \times \mathbb{R}^m,$$

holds. Let  $\{Y_1(t), \dots, Y_n(t)\}$  be a principal system for  $L_n$  and  
let  $\{Z_1(t), \dots, Z_n(t)\}$  be a principal system for  $M_n$  defined by  
 (21). Suppose that

$$\int_a^\infty Z_1(t) q(t) dt < \infty \quad \text{and} \quad \int_a^\infty Z_1(t) |f(t)| dt < \infty$$

hold, then every proper solution  $y(t)$  of (9) satisfies

$$y(t) = o(Y_n(t)) \text{ as } t \rightarrow \infty.$$

C) NONOSCILLATION THEOREM

We consider the equation

$$(23) \quad L_n y(t) + a(t)Q(y(h_1(t)), \dots, y(h_m(t))) = 0,$$

where  $a, h_j: [a, \infty) \rightarrow \mathbb{R}$ ,  $1 \leq j \leq m$ , and  $Q: \mathbb{R}^m \rightarrow \mathbb{R}$  are continuous.

THEOREM 8. Suppose that (11) holds,  $Q(y_1, \dots, y_m)$  is bounded and

$$Q(y_1, \dots, y_m) = o(|y_1|) \text{ as } y_1 \rightarrow 0.$$

If in addition

$$\liminf_{t \rightarrow \infty} \frac{1}{p_0(t)} > 0 \text{ and } \int_0^\infty K_{n-1}(t)|a(t)|dt < \infty,$$

then all proper solutions of (23) are nonoscillatory.

REMARK. This contains the result of [11].

\*\* A part of this talk shall be published in [8].

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